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The Secure, Transportable, Autonomous Reactor (STAR): A Small, Proliferation-Resistant Reactor System for Developing Countries

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Executive Summary

The Secure, Transportable, Autonomous Reactor (STAR), is an integrated concept for a small, proliferation-resistant nuclear power system capable of meeting the growing power demands of many regions of the developing world. The STAR approach builds on earlier work[1, 2] investigating the features required for implementation of such a system. The STAR approach includes establishing overall system requirements, conducting research into issues common to four reactor concepts (gas, liquid metal, light water and molten salt), and defining and performing the down-selection to a preferred concept that will serve as the basis for continued development leading to an eventual prototype.

The paper indicates that a number of unique and distinguishing innovations are needed to both meet the energy demands of most of the world's developing regions and address growing nuclear proliferation concerns. These technical innovations form much of the basis underlying the STAR concept and include:

- Eliminating on-site refueling and fuel access
- Incorporating a systems approach to nuclear energy supply and infrastructure design, with all aspects of equipment life, fuel and waste cycles included
- Small unit size enabling transportability
- Replaceable standardized modular design
- Resilient and robust design concepts leading to large safety margins, high reliability and reduced maintenance
- Simplicity in operation with reliance on autonomous control and remote monitoring
- Waste minimization and waste form optimization

The combination of these features, including the small unit size (on the order of 300 MWt), makes such a system particularly attractive for siting in regions lacking critical infrastructures, such as large established power grids or highly trained construction and operating personnel.

Elimination of on-site refueling and spent fuel storage avoids the dominant proliferation risk associated with existing large nuclear power plants. The avoidance of on-site refueling accomplishes several meaningful goals directly related to proliferation resistance of the reactor system itself, and provides ancillary benefits such as the elimination of the safeguards, security and proliferation concerns associated with spent fuel storage in the developing country; removal of the need for the significant infrastructures involved with refueling; and the reduction of the physical size, mass and cost of containment structures. It also eliminates the need for in-vessel access, further enhancing safeguards. However, such a requirement can only be accomplished by developing very long-lived cores, and this requires innovation in fuel, cladding and structural materials, advances in control and reactivity-compensating materials, and development of new techniques and models for the prediction of materials behavior and design performance.

Prior work identified the major innovations needed to meet the overall goals of a small reactor development and concluded that reactor concepts based on cooling by water, liquid metal, gas and molten salt all have promise of meeting the challenges. All four of these concepts have a common set of crosscutting issues (including manufacturing, transportation, economic feasibility, safety, waste management/spent fuel disposition, regulatory process) requiring new systematic approaches. The STAR development project must manage not only the integrated set of technical R&D activities, but also international participation.

The STAR development project is envisioned to consist of three phases leading to a preliminary system design in five years. In the first phase (lasting approximately18 months), detailed system requirements will be developed, feasibility issues will identified and addressed, and a technology down-selection to one or two candidate systems will be performed. In the second phase (also lasting approximately18 months), the technology research and development program needed to perform a final conceptual design will be identified and implemented. In phase 3 (lasting 2 years), the final conceptual design will be completed. The goal is that at the end of the five-year program, all the necessary information will be in place to allow initiation of detailed design and development of a prototype.

1. Background and Introduction

Energy demand in the developing countries is increasing concurrent with their growing populations and economies, and this demand is expected to continue to grow at a rapid pace well into the next century. This demand will be met by a combination of fossil, renewable and nuclear power sources. However, the current mix of these energy sources does not, and can not, satisfy all demands for new energy. Fossil fueled sources add to the accumulation of greenhouse gases and are of limited supply in many areas. Renewables, including hydro, are in limited supply, or are at an insufficient level of technical readiness to play a major role in meeting energy demands. Today's nuclear systems are too large and expensive for many areas, especially those lacking the necessary institutional infrastructure, expertise, capital or large established power grid. A small nuclear power system could provide an ideal solution for meeting the needs of many regions for which these current systems are inadequate.

A recent survey[3] completed by the International Atomic Energy Agency (IAEA) indicated that not only is the need for such systems real but that by the year 2015, developing countries are expected to need 70-80 small and medium sized reactor systems. Currently, other countries are developing small reactors for this potential commercial market. For example, South Korea has been developing a concept known as SMART; and Argentina has been developing concept known as CAREM. Both of these systems are based on down sizing today's large light-water reactor technology to make it suitable for small power levels. China is developing a small high temperature gas cooled reactor for seawater desalination and process heat. These efforts tend to focus on the development of the reactor without integrated considerations of the overall fuel cycle, proliferation or waste issues.

The U.S. government also recognizes the needs of the developing countries. Current U.S. foreign policy on nuclear issues is dominated by proliferation and nuclear safety concerns. Recent events in India and Pakistan have served to re-focus world attention on the threat of proliferation. In its April 1998 Comprehensive National Energy Strategy[4], the Department of Energy called for "research into low-cost, proliferation-resistant, nuclear reactor technologies" to ensure that this demand can be met in a manner consistent with U.S. non-proliferation goals and policies.

In the STAR project, we propose to develop a system that meets stringent requirements for proliferation resistance, achieves a high degree of safety with a minimum reliance on maintenance and supporting infrastructure, and also deals directly with the related nuclear waste and spent fuel management issues. This effort has two primary thrusts: first, the development of a small, proliferation-resistant nuclear system (i.e., a technology focus); and second, the continuation of open communication with the international community through early engagement and cooperation on small reactor development.

A reactor on the order of 300 MWt appears to have the best potential for meeting these challenges. The system will have unique characteristics to achieve proliferation resistance, and will maximize the reliance on passive safety features to reduce the risk of serious accidents and their consequences, simplify operations and maintenance, and reduce the need for the developing country to establish a sophisticated and expensive nuclear infrastructure.

In particular, the reactor will be designed to achieve a high degree of proliferation resistance by eliminating all on-site refueling. The system will be installed as a complete unit and, following completion of its planned core life, will be returned to the supplier under international control. This approach not only furthers the overall non-proliferation objectives, but also allows operation with a reduced infrastructure burden on the developing country. It also potentially allows a reduction in the anticipated burden and expense for assuring safeguards and security associated with expanded international use of nuclear energy. An integral part of the effort will be the development of new approaches for the implementation of international safeguards applicable to the entire fuel cycle, including recycling and waste disposal.

Development of a small, modular nuclear power system offers promise as a viable alternative to either the capital intensive large nuclear systems or the environmentally problematic fossil fuel systems likely required by developing countries to meet their growing energy demands. Our objective is to develop a system featuring unique design elements that overcome many of the barriers to implementation of nuclear power systems in many parts of the world. Elimination of on-site refueling through a combination of long-life cores and small systems with replaceable modules reduces proliferation concerns, especially those related to spent fuel storage. Small, transportable modular designs, and designs focused on a high degree of autonomously safe operation significantly reduce infrastructure and construction requirements of the host country, and contributes towards significant reductions in initial capital and operating costs. Small unit power levels makes the system compatible for areas lacking the large electrical grids normally associated with today's nuclear systems. Finally, the approach should significantly reduce the projected cost of providing IAEA safeguards for the anticipated growth in international use of nuclear power.

2. Systems Approach

Successful development of a small reactor system of the type envisioned here requires a comprehensive systems approach that considers all aspects of manufacturing, transportation, operation, and ultimate disposal. Such an approach has been used extensively in the development of space nuclear power systems. The U.S. aircraft industry also uses such an approach in the production of new aircraft and this experience may be most suitable for the small reactor modules envisioned.

The systems approach used in the development of space nuclear power systems included consideration of many diverse requirements, such as: no planned maintenance; highly reliable autonomous operation for a long period of time; no refueling; and ultimate disposition. While the engineering designs used for space nuclear power systems are not directly applicable to terrestrial applications, the systems approach itself offers many advantages to the development of new terrestrial systems suitable for developing countries.

Applying this system design concept to development of small nuclear power systems and achieving acceptable economics is very challenging, but it could have major advantages. For example, by considering the entire life cycle of the system, significant reductions in the generation of radioactive waste can be achieved for the system as a whole, rather than the usual practice that often results in one waste minimization activity actually increasing wastes farther along in the system.

Considering the complete fuel cycle and impeding access to the fuel by eliminating on-site refueling appears to have the potential for significantly improving proliferation resistance. Such a system would simplify safeguarding the fuel and could provide a basis for development of new policies for addressing the back-end of the fuel cycle.

3. System Requirements

Our principle objective for this concept is to achieve a system that can provide a secure, safe and affordable nuclear energy supply to countries with critical energy needs but insufficient resources to support them. The following requirements outline how these advantages may be achieved. The "system concept" we have in mind is specified by a set of the key system requirements. This set of preliminary requirements includes the following:

- The nuclear reactor should be delivered to the site already assembled. Most importantly, this also means the reactor should be already fueled when shipped to the site. If shipping an already-fueled reactor is precluded by safety or technical considerations, fueling must be accomplished under strict international control, and means to effectively seal fuel in the vessel and eliminate further on-site access into the vessel must be provided.

- Highly autonomous operation. All operations, from initial start up to final shutdown must be as autonomous as possible. Operator actions could be limited to pressing a button to start the nuclear system and those actions necessary to operate the power conversion or other non-nuclear systems. For the remainder of the operational life, the operator's primary function should be to monitor the status of the system. Advanced instrumentation and control technologies coupled with the anticipated improvements in inherent reactor control mechanisms in these low-power systems make realization of such goals possible. There would be significant cost savings associated with reductions in the number of highly trained staff at the site.

- Reliance on passive safety mechanisms. All credible failures should be safely terminated by passive mechanisms in the nuclear system and be terminated without the release of radioactivity to the power system site. Postulated severe accidents should be terminated without requiring emergency off-site responses. An approach to recover from such postulated situations that permits recovery of the site should also be identified. This capability is a necessary corollary to achieving the staff reductions envisioned above.

- Planned maintenance should be limited to non-nuclear, or electrical and control components easily accessed outside the reactor enclosure. Special attention must be given to eliminating instrumentation that is inherently short lived because of temperature or radiation damage.

- Replacement and disposal must be integrated into system design. One of the features inherent in our concept of no on-site refueling is that at the end of its core life, the entire reactor module is replaced. Careful design, incorporating the replacement, reconditioning and disposal of expended reactor modules, including disposition of spent fuel is an important goal.

These are especially demanding goals that are likely to be achievable only with power systems that are of relatively low power compared to the large plants commonly used today. However, satisfying them has the potential to increase security, safety and public acceptance of the expanded use of nuclear power within developing countries. We recognize that one of the major challenges will be to accomplish these goals with an economically viable system. Today's approach to nuclear power economics relies on the economics of scale. Our concept approaches the economic issue from a different perspective: we implement the economics of mass production, coupled with cost savings achieved from dramatically reduced on-site installation, operation and decommissioning costs, reduced site infrastructure requirements and substantial improved approach to licensing to overcome the loss of economics of scale.

4. Application Potential

The STAR system is targeted for the developing regions such as South East Asia, Sub-Sharan Africa and South and Central America. There are countries within these regions that have high population growth and are also working to raise their standard of living. The electric power grids in some of these areas are also minimal. In addition, because of geographical isolation or lack of indigenous alternatives, nuclear power may be a viable alternative. Several countries (e.g., Russia, South Korea, South Africa, Argentina, China) are developing concepts that could be used in these applications, however they are not giving the emphasis to proliferation resistance being required here.

Projected population growth for these countries will be well over 250 million by 2025. For their standard of living to improve to half the average of the developed countries, approximately 1KW of new generating capacity per person will be needed. This means that some 250 GWe new capacity will be needed, the equivalent of two hundred and fifty 1000 MWe plants, or twenty five hundred 100 MWe plants. Continued growth in population and their standard of living will double this estimate by 2050. Much of this capacity will be met with conventional technologies, including large nuclear systems. Even with these other systems, the IAEA estimates that 70-80 small-and-medium reactor systems will be required by 2015. With even greater growth anticipated beyond 2015, the potential outlook for such systems is optimistic, and could require production rates on the order of 10 or more plants per year.

5. Safety Concept

Two very demanding safety requirements have been identified. Firstly, all credible accidents (those considered to be within the design basis) should be safely terminated by passive mechanisms in the nuclear system. By "safely terminated" we mean not only that the consequences of such events must not only be limited to the site, but also that such events do not result in life-limiting damage to the systems and that there be no radiological consequences to the on-site staff. Secondly, postulated severe accidents (those beyond the design basis) must be terminated without requiring emergency off-site responses. These postulated events should be consistent with known physical principles, but would include operational failures coupled with postulated failures of protective features and equipment. An approach to recover from such postulated events, which permits ultimate recovery of the site, should also be realizable. That is, bounding accidents should not result in loss of the use of the site due to contamination. These two requirements are key to achieving the operational and design simplifications desired in the nuclear systems.

The small unit size and low unit cost of this approach presents a unique opportunity to perform a much broader range of safety verification testing than is afforded by conventional nuclear designs. This level of testing would provide a full-scale demonstration of the ability of the design to achieve the required safety envelope. Certification of the design by testing, including severe accident testing, would contribute broad acceptance for use of the system in developing countries. Such an approach also supports licensing certification by test as once proposed to the NRC[5].

Safety certification of the design would be completed by the supplier, similar to what is done with commercial aircraft. Licensing the use of a factory fabricated standard design in many different countries would then be much like approving use of certified aircraft. The regulatory burden on the user country would be substantially reduced as well as the cost per each unit produced.

Reliance on a high degree of autonomous operation, achieved through a combination of passive, inherent physical responses and advanced control systems, minimizes the potential for human error initiating or exacerbating off-normal events or accidents. It also reduces the training and regulatory burden on the user country. Far fewer nuclear specialists are necessary to approve and operate such systems. Similarly, eliminating the need for on-site refueling and minimizing on-site maintenance further reduces the need for a supporting infrastructure in the host country; such maintenance services can best be handled by a single supplier service organization consisting of very highly trained and skilled professionals who would provide essentially all repair and maintenance functions for the entire fleet of these standardized facilities.

6. Operational Concept

The infrastructure necessary to support conventional nuclear power development is very expensive, and beyond the resources of many or most of the developing countries. One of the primary goals of proposed approach is to reduce the need such an infrastructure. The system requirements of highly autonomous operation, simplified and minimized system maintenance and elimination of all on-site refueling all significantly contribute to this goal.

To some extent, the complex nature of today's nuclear energy systems is a result of the many support and safety systems, often redundant, needed to ensure the safety of these very large, high power systems. Many of these systems can be reduced or eliminated with smaller systems, where natural forces (such as natural circulation flow) are sufficiently strong to satisfy many safety and operational criteria. A more aggressive approach to simplifying the system is being used to support both large reductions of on-site staff and the technological infrastructure necessary to support operation, maintenance and regulation. If the ultimate in reliability and simplicity of operations can be achieved, it may be possible to reduce the nuclear staff per shift to a couple of people in the main control center and a minimum electrical maintenance staff.

Nuclear instrumentation and control devices present the greatest challenge. Even though it may be possible to develop a system that is inherently controlled by temperature over the normal power operating range, it appears that it will always be necessary to include control devices and instrumentation in the nuclear system to adequately control and monitor start up from cold shutdown, total shutdown, and possibly to compensate for fuel burnup. Design configurations that reduce the number and complexity of these instrumentation and control components need to be developed.

Typically, the conventional power conversion components of a plant include dynamic machinery and numerous active control mechanisms. It will be nearly impossible to avoid planned periodic maintenance on this equipment. Even though it is likely desirable to simplify and reduce the staff and infrastructure needed for this portion of the plant, the technical expertise and infrastructure required for effective maintenance and operation of these systems can likely be shared with that needed by other, more conventional power generating systems the developing country will also have. Depending on the specific configuration of the system however there may be a cost or operational benefit that may demand supplier servicing of selected components within the power conversion portion of the plant. Ideally, a plant that required no operating staff on site would certainly be desirable.

7. Manufacturing

The importance of a totally new approach to manufacturing of the small reactors, not just modularization, can not be over emphasized. The concept of "designed-in manufacturability" can result in significant cost savings, particularly when amortized over a large number of systems. The goal of producing a system that can be easily transported and installed can also contribute to manufacturability, as this goal leads directly to components having more "reasonable" size and mass than found in today's large nuclear power systems.

An aggressive approach to factory assembly of the plant and shipping of modules that can be quickly installed at the site will be necessary to control costs to an acceptable range. The factory production line will need to be designed as an integral part of the product in a manner similar to how Boeing produced their 777 model. The plant would be based on production of many hundreds of essentially identical modules. Ideally, three or four major assemblies would be fabricated, quality inspected and tested prior to shipment. With exception of the nuclear assembly and its auxiliary systems and components, these types of major assemblies have been demonstrated with the large diesel and combined cycle plants that have technology complexity not that different from the nuclear plant desired.

Simplification of the system design coupled with factory manufacturing of standard modules may make it possible to challenge the economy of scale with the economy of mass production. As discussed later it will be necessary to identify a large stable market to support this approach.

8. Delivery and Installation Concepts

Transportation and installation of barge- or ship-mounted small nuclear power systems is clearly feasible. Designs for barge-mounted "conventional" nuclear systems were developed in the early 1970s, and even today, ship mounted small reactor concepts are being proposed.

However, it is also desirable develop a system concept that is also amenable to land-based siting, including the need to transport the modules overland. This desire will place additional constraints on the size and mass of the individual modules making up a full system, especially when one considers that supporting transportation infrastructures in the developing countries (roads, railways, etc.) may be substandard or even non-existent. These considerations strongly suggest that design of special transport and handling equipment and procedures be integrated into the overall system design.

While it is likely that barge- or ship-mounted systems can be optimized at larger powers than their land-based cousins, we believe the advantages provided by mass production of highly standardized units will eliminate any minor cost advantage a larger system might enjoy for barge-mounted applications.

The transportation systems for removing the spent reactor modules present a great challenge. The problem of shipping a highly radioactive component either on land or by sea must be addressed, and associated environmental concerns will influence how the nuclear system is designed. For example, capability for recovery of a sunk shipment from the ocean bottom may be a requirement, and could have a strong influence on the nuclear module designs, even for those installed in barges or submersibles. The possible need for additional shielding, especially for overland transportation could have an impact on the size of the nuclear module originally installed and could cause it to be quite small.

Another important requirement related to the removal transportation, is the time period permitted between final shutdown and required removal. Because of the intensity of radioactivity and decay heat in the nuclear module immediately following shutdown, it would be preferable to leave the shutdown module in place for many months. While potentially unavoidable, such a post-shutdown delay would likely complicate replacement of the reactor module, particularly for sites with limited real estate. Although there may be a slight reduction in proliferation risk by removing the spent nuclear module soon after shutdown (as opposed to later), we believe that the difficulty associated with removing or accessing a spent reactor module to be a sufficient deterrent. Rapid removal/replacement of a spent reactor module might be accomplished sooner with the barge- or ship-based systems, but unless the installation allows separation and replacement of the nuclear system it would mean that there will be a significant investment in power conversion equipment that is unused while in transport or being refurbished. This may not be a great penalty if the on-station time for the system is in the range of tens of years.

These and many other broad system issues will be the topics of the trade studies necessary to identify the preferred system. It is clear that manufacturing, delivery and installation constraints will have an important impact on reactor size which in turn may vary depending on the selected nuclear system technology.

9. Recycling and Waste Disposal

One of the important aspects of our systems approach is that disposition of waste and recycling of usable components is integrated into the design of the overall system, including materials selection and mechanical design. It is our intent that the nuclear reactor module, or (possibly in the case of barge mounted systems) the entire plant would be shipped to an internationally monitored site for refurbishment of usable components, recycling of highly valued materials and the preparation of waste materials for permanent disposal.

The characteristic of the "refurbishing" site and its facilities must also be integrated into the overall design, and will take into account spent fuel processing, waste treatment and disposition of other materials and components. The extent to which other equipment is refurbished may also influence the character of the site. A barge-mounted system might be likely to have the entire system refurbished and therefore the site would need to consider this entire refurbishment activity.

One of the more difficult issues associated with recycling and waste disposal is not a technical issue, rather it is a political and institutional issue: how to deal with wastes, especially nuclear wastes, resulting from operations in a foreign country. The U.S., as well as most other countries, have restrictions on the acceptance of nuclear waste from other countries. It is possible that new national and international policies, treaties and laws may be necessary to gain all the advantages that such a centralized approach might afford.

10. Safeguards Aspects

Safeguards provide two essential functions for the nonproliferation regime: it provides assurance that facilities and materials are not used for illicit purposes, and it provides timely warning of an event taking, or having taken place. The proliferation risk associated with a nuclear system derives from four aspects:

- attractiveness of fissile materials;
- accessibility of the materials;
- utility of the facility for illicit purposes (for example, irradiation of fertile materials); and
- size and character of the infrastructure needed to support using the nuclear system.

Traditional power systems are quite proliferation-resistant. Their fresh LEU fuel is of too low enrichment to be directly used as a nuclear explosive. The reactors are ill suited for illicit irradiation and production of weapons material. Plutonium in spent fuel has poor isotopics for weapons application, and is inherently protected by the significant radiation field arising from the fission product inventory. Even so, safeguarding of LWR plants is needed because none of these barriers to proliferation risk is, by itself, completely effective. Diverted fresh fuel could be used to reduce the enrichment effort, given appropriate facilities. Fertile materials could, with difficulty, be irradiated in LWRs. The radiation barrier inherent to spent fuel decays with time, and plutonium from LWR spent fuel is considered a weapons-useable material.

The elimination of on-site refueling directly attacks the least proliferation-resistant attributes of the traditional power reactor, accessibility of materials and use of the facility for illicit purposes. Elimination of on-site refueling removes easy access to both fresh and spent fuel from the reactor site. Fissile material is found only inside the reactor, where it is protected by both problems of physical access and a very intense inherent radiation barrier. The only period where fissile materials might be considered at risk is during transportation, set up and during early operation, where the fission product buildup is limited. Access to fissile materials and use of the reactor for illicit irradiation is further complicated by the lack of physical features and infrastructure to open the reactor vessel.

In addition to the direct reduction of proliferation risk resulting from the elimination of on-site refueling, the need and complexity of on-site surveillance can also be reduced. With no on-site fresh or spent fuel storage, the need for active and/or periodic monitoring of fuel stores is eliminated. The very lack of a refueling infrastructure implies that the time necessary for opening the reactor vessel to gain access to fissile materials is likely so long that the very act of shutting the reactor down may serve as the primary alert indicator. This offers potential for simplified safeguards and security that, in the limit, might require only monitoring that the reactor is indeed operating. This could even be accomplished or augmented remotely, perhaps using satellite platforms to monitor the IR signature of the facility.

The high degree of autonomous automation desired for these systems offers three additional benefits to a new safeguards environment. First, such autonomous operation offers opportunities for remote monitoring and diagnostics that may be exploitable to assist safeguards monitoring. Second, such design offers the potential for reductions in system transients and resulting shut-downs. In such an environment, any off-normal event becomes a potential safeguards alarm. Finally, the combination of autonomous operation and elimination of on-site refueling reduces the infrastructure, including personnel, available to support illicit activities.

11. Technology Options

This section summarizes a preliminary assessment of the design approaches that various technologies might take to achieve the requirements. The discussion is based a preliminary assessment of the strengths and weaknesses each technology offers in meeting the requirements, and a cursory look at how these strengths and weaknesses might be exploited or mitigated. This assessment is only intended to provide an approximate prioritization of the concepts; each concept will be reviewed in greater detail as part of the overall program. The technologies are addressed in their current order of preference, based on their likelihood of meeting the no on-site refueling requirement with practical limits on development cost and schedules.

Liquid Metal Cooled Systems.

Liquid metal cooled reactors (LMR) have been under development for more than 40 years, and several have been built and operated on commercial power grids. Sodium has been generally used as the coolant in these systems, and experience with this technology has been mixed. Sodium leaks have been the most notable technical issue, and the fact that sodium is very chemically reactive with air and water has contributed to most of the concerns about LMRs. In the past few years the Russians have reported experience they have had with a lead-bismuth alloy coolant in submarine propulsion reactors. Because this coolant is not chemically reactive with air and water it provides a significant improvement over sodium, but has other issues, notably materials compatibility issues. The technology is clearly still developmental even though there is considerable valuable experience.

Concepts based on fast LMRs have high internal conversion of fertile to fissile material and therefore have the potential for long core life without initially high reactivity that requires some form of poison compensation. LLNL and the University of California have developed some variations on the Japanese 4S concept that could extend its neutronic life to more than 15 years.[1,6,7,8] There are unanswered concerns however about the clad and structural damage from large neutron irradiation, but the results of this preliminary work are encouraging.

Fuel systems for LMRs are well developed, and the use of oxide, carbide, nitride or metal fuels has been demonstrated and provides many options for addressing the long life requirement for the fuel. Metal fuels, in particular, offer promise of improved safety characteristics.

Liquid metal cooled systems operate at low pressure and have very large thermal margins relative to their boiling temperature. There is negligible thermal energy stored in the coolant available for release in the event of a leak or accident. This translates to the potential for compact system designs, including the containment. In addition, the large thermal expansion coefficients of liquid metal coolants inherently support good thermal characteristics for natural circulation cooling and provide very favorable passive safety characteristics.

The sodium coolant used by most LMR developers has created some safety concerns because of its chemical reactivity with air and water. Lead, lead-bismuth or other alloys of lead appear to eliminate these concerns because the chemical reactivity of this coolant with air and water is very low. It may also contribute to system simplification by eliminating the need for the intermediate coolant loop required with sodium. The Russians have extensive experience with this coolant and when it is combined with the

Japanese 4S configuration it conceptually is a very attractive system. Several major issues must be addressed, however. The most important of these appears to be materials corrosion. This is a serious issue, and although the Russians have had success in this area through monitoring and control of the oxide content, long-term materials compatibility must yet be established.

Extensive development and demonstration work, beyond that required for a small LWR based concept, may be required. These reactors also require fuel that is enriched to nearly 20% and therefore fuel recycling is most likely necessary to achieve economic performance. Because of the developmental uncertainties and the possible need to include fuel recycling in the system, the cost of implementing a system design based on liquid metal coolant is uncertain.

Gas Cooled Systems

Gas cooled reactors, although not extensively used for electric power generation, have continued to be used and receive developmental attention. There have been many years of successful power operation on the power grid in England. Helium has become the coolant of choice in the high temperature versions of this technology. Recently, development work has focused on modular reactors coupled to gas turbines to improve both economics and the passive safety characteristics. Considerable effort has been invested in development of graphite coated fuel particles that are imbedded in a graphite matrix. However, there is also considerable experience with cermet fuels which have fuel particles imbedded in a metal matrix. This later technology has not received much commercial attention, but has had extensive development completed for application to aircraft and space systems.

There is some continuing interest in gas cooled reactors South Africa, China and Russia. ESKOM, the South African state operated utility, is interested in a high temperature gas cooled reactor combined with a direct cycle gas turbine for powering rural areas that currently are without electricity. They have developed a preliminary design for a system based on the pebble bed reactors developed in Germany. General Atomic and Russia in cooperation with others have also completed a study on design of a gas cooled gas turbine plant for use in Russia. China has operated a 5 Mwt gas cooled reactor and has plans for construction of a 200 Mwt system that is intended for process heat applications.

Since gas cooled reactors are predominantly thermal spectrum reactors, the challenge will be to develop a concept for extending core life. De-rating the fuel and operating the reactor at lower power densities than under optimum operating conditions is one possibility. This could have an unfavorable impact on economics. Thorium fuel cycles have been applied to these types of reactors and could be used contribute to increased core lifetime. However the emphasis with the pebble bed reactors have been to use on-line refueling in which pebbles are added and removed on a frequent basis. There have been conceptual designs for pebble bed reactors that only partially fill the reactor vessel at the start of life and gradually add fuel thus extending reactor life. Consideration could be given to hardening the spectrum and improving the internal conversion, possibly even using cermet fuel in a fast spectrum reactor.

The modular designs that have been study in recent years have very favorable passive safety characteristics. Both the Russian and Eskom designs incorporate robust passive safety capability. Even though the systems run at high pressure, there is little energy stored in the single phase coolant and the thermal margins in the fuel are very large, and a loss of coolant accident may be accommodated passively. However, containment design continues to be question and may add to system size and complexity.

The direct cycle gas turbine is the most attractive configuration for the gas technology. Inclusion of steam generators contributes complexity and decreases efficiency and reliability. Even though there has been no operational experience with a direct cycle gas turbine HTGR (and therefore development cost and risk are high), once developed it is expected to be very economical. This is a viable candidate and considerable progress has been made in this technology but it requires demonstration.

Light Water Cooled Systems

The LWR is the most highly developed and deployed reactor and fuel cycle system in the world. Many small versions have been designed and even deployed, although most have been limited to submarine versions and other special purposes where the economics have been a secondary requirement. The possibility of adapting various highly developed marine systems to small electric generator designs is being seriously considered as a viable option.

The main challenge facing this technology will be to extend the refueling interval much beyond 2 years while maintaining the inherent safety objectives. Power de-rating, similar to the gas reactor can extend core life at the expense of increases in power cost and the physical size. There are efforts underway to extend fuel life to three years, but it is likely to require much further extension to make this technology viable. Long-term autonomous control may also be a challenge, partly due to reactivity changes over the life of the plant, and partly due to other technical issues such as the need to maintain water chemistry and pressure control.

The small units can be made simpler and include large margins to safety. Natural circulation cooling at full power is possible. However, because of the large amount of stored energy in the coolant a pressure retaining containment is necessary to meet the safety objectives. It is also likely that active safety components such as isolation valves may be required.

LWR technology is the most developed technology and therefore may have very low development cost. However, significant development to achieve the long fuel lifetimes required here may offset the economics afforded by the mature underlying technology base. Additionally, the high system pressure and significant thermal energy stored in the coolant complicates safety and containment design, and is expected to increase system size, mass and cost.

Molten Salt Systems

There has only been one molten-salt reactor system constructed, and although its experimental operations were successful there have been no others. The interest has been largely academic, but conceptual designs of commercial plants have been developed. This technology would require the largest development and demonstration program, and with no licensing experience could prove to be a difficult option to implement.

One of the major concerns about this technology, besides the limited technology base, is the lack of materials with demonstrated long-term compatibility. Long-life operation will require on-line chemistry control and processing of the molten-salt fuel, and although demonstrated at the laboratory level, such processing remains a development issue.

The fact the molten salt concept offers promise for long reactor life through automated fuel processing and management is the primary basis for interest in this system. Automated additions of fuel and removal of the fission products, if possible, could remove fuel life as a limiting factor to system life. Such automation is clearly a major challenge.

Because the reactor can be designed with very little excess reactivity in the core and the molten salt has very good heat transport characteristics, the potential of achieving the passive safety objectives also exist. The facts that 1) the molten-salt reactor is a low pressure system, 2) the coolant is very chemically stable and does not react with air or water also support the passive safety characteristics of this concept.

However, the fact that the fuel is both mobile and unclad makes for serious concerns about fuel leakage and for containment and control of the gaseous fission products. These concerns will impact the designs of containment and fuel chemistry management systems, and may require significant developmental efforts to demonstrate.

This technology is clearly very speculative and would likely require the most development and demonstration. The cost and schedule for implementing a concept based on this technology may also be the most demanding. With innovation however, it may be possible through use of automation to realize a design concept that best addresses functional requirements.

Other Technologies

We have briefly reviewed other technologies, such as heavy water reactors but have not identified any that have sufficient merit to warrant their consideration. The CANDU-HWR is well developed but uses on-line refueling which is contrary to the objective of excluding on-site refueling.

There are LWR and LMR advanced fuel-cycle schemes being investigated that have the potential to improve the proliferation resistance of current reactors. However they usually require extensive fuel shuffling or modifications of the fuel to make the fuel less suitability for weapons application. These approaches may be found to be suitable for large reactors but they do not appear compatible with small reactors that have a requirement of no on-site refueling.

12. R&D Issues

The proposed program for designing a new, proliferation-resistant reactor is based on a bottoms-up approach. That is, we believe it imperative to develop a consistent, well thought out set of performance, design and operational criteria that truly reflect the goals of the program rather than to make marginal improvements to existing systems. Even though the latter approach has clear short-term advantages in terms of development effort, cost and schedule, we believe the marginal improvements in both proliferation resistance and fundamental safety are insufficient to support broad institutional acceptance of such designs.

While it is possible that systems based on existing technologies may be conceived that meet the objectives, it is likely that an extensive R&D effort will be required. Without clearly defined concepts, we can only outline the general scope of such a program. In fact the development of the system concepts is the first major program objective.

Clearly, systems designed for long-term operation without refueling will place new demands on fuels and in-core materials compatibility and performance, and will demand improved analytic techniques, including nuclear analysis and structural performance methods. Desirability of transportable designs may require new methods of manufacturing, transport and installation. New approaches to siting and design certification, perhaps through new international institutions, could facilitate a broader acceptance of such systems and installations, and further help minimize infrastructure development of the host country. Implementation of highly reliable automated controls that rely on a minimum of instrument signals will need to be developed.

13. Approaches to Financing

The financing of the initial research necessary to realize a small reactor concept for developing countries is under discussion. We are seeking to involve international participation early in the program as advisors, and as the program matures the international participation and funding would be expected to increase. The program being proposed would include two major phases lasting approximately 12 years. The first phase of 5 years would lead to a conceptual design of a preferred and backup system. The first phase would be financed by the participating governments. The second phase would provide a prototype for certification testing. This phase would also be expected to have major government participation for the certification testing, but would use commercial support for establishing the production facilities. These facilities would be used to produce the prototype as well as the subsequent production models. It is envisioned that the program would shift from largely government supported laboratory research into a partnership with industry that would lead to the facilities operated by industry and internationally monitored. These facilities would include the factories and production lines to produce a standard set of assemblies suitable for use at a wide range of sites.

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Development of a New Reactor Concept:
An Advanced, Low Power Nuclear System with Enhanced Proliferation Resistance

The Need:
A small, proliferation resistant, nuclear energy supply option:

- *Rapid worldwide growth in energy needs over the next 30 years, especially in developing countries.*
- *Limitation of atmospheric emissions will lead to the selection of nuclear power for this market.*
- *Several countries (Argentina, Korea, Japan, and Russia) are currently working on small reactors.*
- *These other concepts do not include non-proliferation as a design requirement.*
- *The US can influence nonproliferation goals only through our own small reactor development.*

STAR

The Secure, Transportable, Autonomous Reactor

Key *STAR* Program Goals:
Develop a small nuclear plant for developing countries that is:

- *Proliferation-resistant*
- *Safe*
- *Environmentally sound*
- *Economically competitive*
- *Compatible with indigenous infra-structure*

Our Approach:
Integrated, multi-participant program to achieve the key goals:

- *Proliferation-resistance: No on-site access to fresh or spent fuel*
- *Safety: Passive safety; highly autonomous control*
- *Environmental approach: secure retrieval of spent reactor fuel at central facility; design for D&D; no CO_2 emissions*
- *Economic competitiveness: simplified design; mass produced; modular delivery*
- *Compatibility with indigenous infrastructure: small system; autonomous control; use for electricity, desalination and/or district heat.*

Our Team: *A consortium of highly respected National Laboratories, Universities and Industry.*

Lawrence Livermore National Laboratory

- National Labs
  - •LLNL
  - •Argonne
  - •LANL
- Industry
  - •Westinghouse
- Universities
  - •MIT
  - •Texas A&M
  - •UC Berkeley

Major Benefits to DOE:

- ✓ *Development of advanced concepts*
  - *Proliferation resistant reactors and fuels*
  - *Advanced lower-power designs*
  - *High efficiency fuels*
  - *Reactor materials research*
- ✓ *Collaboration between US universities, national laboratories and industry*
- ✓ *Technology transfer to the civilian sector*
- ✓ *Active international cooperation*
- ✓ *Maintain vital research infrastructure*

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